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<p>This is a final report on the research project "Large Scale Forcing and Oceanic Response". The objective of the program was to examine the coupling between the atmosphere, the oceanic mixed layer, and the interior of the ocean on large scales in the eastern North Atlantic. To accomplish this field work was done in the eastern North Atlantic to: 1) make high quality, direct observations at widely spaced surface moorings in the Subduction and ASTEX (Atlantic Stratocumulus Transition Experiment) region of the surface forcing (wind stress and buoyancy flux) fields; 2) observe the oceanic velocities and temperatures at these sites, resolving the vertical structure of the upper ocean and its temporal variability over two annual cycles; 3) collect sufficient information about the surface forcing and upper ocean structure at sites between the moorings to allow extrapolation over the whole Subduction region of the description of the mixed layer response to atmospheric forcing; 4) observe at a site central to Subduction the response of the thermocline and the interior of the ocean as well as of the mixed layer. Analyses and modeling work followed the field work with the goals of examining air-sea interaction on a large scale, looking particularly at the convergence of mass and heat in the mixed layer associated with basin-scale gradients in atmospheric forcing and the resultant pumping of the interior of the ocean.</p>			
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Final Report: Large Scale Forcing and Oceanic Response (ONR N00014-90-J-1490)

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This project ran from 1990 to 1997. In the first 4 years the focus was on work in the field as part of the Subduction Experiment, including the deployment for two years of an array of five surface moorings in the eastern North Atlantic. In the last 3 years the focus has been on the analysis of the data collected from that array and on modeling the subduction processes in the eastern North Atlantic. This document serves as a final report to the Office of Naval Research marking the end on December 31, 1997 of the funding for this work.

Our **long-term goal** is to develop an improved understanding of how the ocean responds to atmospheric forcing. Under study are: the role of mesoscale and submesoscale oceanic variability in modulating air-sea interaction; the role small scale processes such as Langmuir circulation in the vertical transfer of momentum and other properties down from the air-sea interface and in determining the vertical structure of the mixed layer; the structure and dynamics of the Ekman layer; and how the convergence of mass and heat in the mixed layer associated with basin-scale gradients in atmospheric forcing couples the mixed layer to the interior of the ocean.

Our **objective** under this program was to examine the coupling between the atmosphere, the oceanic mixed layer, and the interior of the ocean on large scales in the eastern North Atlantic. Specifically we sought to: 1) make high quality, direct observations at widely spaced surface moorings in the Subduction and ASTEX (Atlantic Stratocumulus Transition Experiment) region of the surface forcing (wind stress and buoyancy flux) fields; 2) observe the oceanic velocities and temperatures at these sites, resolving the vertical structure of the upper ocean and its temporal variability over two annual cycles; 3) collect sufficient information about the surface forcing and upper ocean structure at sites between the moorings to allow extrapolation over the whole Subduction region of the description of the mixed layer response to atmospheric forcing; 4) observe at a site central to Subduction the response of the thermocline and the interior of the ocean as well as of the mixed layer. The objectives of the analyses and modeling work that followed were to examine air-sea interaction on a large scale, looking particularly at the convergence of mass and heat in the mixed layer associated with basin-scale gradients in atmospheric forcing and the resultant pumping of the interior of the ocean.

Our **approach** was to set and maintain an array of five surface moorings spanning the eastern end of the Bermuda-Azores high for two years, June 1991 to June 1993, working jointly with R. Davis (Scripps Institution of Oceanography). This array was part of the cooperative Subduction experiment, and was designed to span the eastern end of the Bermuda-Azores high. The array provided high quality surface meteorological data at select points in the Subduction region; together with gridded data from numerical weather prediction models this data was used to define the surface forcing fields. Oceanographic instrumentation was deployed on the moorings to collect the data needed to describe oceanic response to local forcing. All five moorings are instrumented with current meters and temperature recorders in the mixed layer. Together with the surface meteorology the upper ocean data was used to quantify the local response. Together with the forcing fields, knowledge of the transfer function describing the relation between

local response and forcing allows estimation of the convergence of mass and heat in the mixed layer over the Subduction region.

The first deployment of the moored array was in June-July, 1991. The elements formed a large square array, spanning 18 to 33 degrees N and 22 to 33 degrees W, with a fifth mooring in the center. The corner moorings were labeled NE, SE, SW, and NW while the central mooring was labeled C. Early failures of the NW and SE moorings required recovery in September and November, respectively. Redesign of the NW, SE, and SW moorings has been done to improve their longevity. Additional data was collected to complement the data from the moorings, including ship of opportunity XBTs and gridded fields from numerical weather prediction models and climatological data bases. The mooring deployment finished in July 1993 when the last of the three 8-month deployments of the 5 element array was completed. Post-deployment calibration of instrumentation followed. Preliminary processing of the data, including quality control was completed in 1995.

Scientific analysis of the moored array data set started by analyzing the atmospheric forcing data from the array in the context of climatological data and gridded fields from the European Centre for Medium Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP). Air-sea flux time series were computed. Climatological data sets and weather maps were obtained and compared with the model fields and the buoy data. A paper was presented at a meeting on in-situ validation of numerical weather prediction models held at ECMWF detailing the comparison of the buoy data and the model and climatological gridded fields. Using adjustments based on these comparisons and the high frequency information from the surface buoys a gridded data set descriptive of the surface forcing during Subduction with 1 degree latitude/longitude and 1 hour time resolution was produced and written to CD-ROM for our use and use by other Subduction investigators.

The oceanographic analysis started with an examination of the response of the upper ocean to local forcing at each of the five sites. The temporal evolution of the

upper ocean at each of the five sites was characterized, and the local forced response at each site identified and contrasted with predictions of various mixed layer models, including PWP (Price-Weller-Pinkel). The buoy fluxes have been used to force various one-dimensional models. The understanding of the forced response combined with the gridded forcing fields yields a two year description of the forced response of the upper ocean over the whole Subduction region. This is contrasted with climatological upper ocean temporal variability and horizontal and vertical structure and with the response to climatologically typical forcing inferred from our understanding of the forced response. Finally, the surface forcing and upper ocean fields are being used to quantify subduction rates and the various contributions to the subduction process.

The analysis of the large-scale, forced response of the upper ocean is in its final phase and being done in the context of a three-dimensional ocean model. This approach allows us to investigate the influences of the three-dimensional advection field, mixed layer physics, interannual and seasonal variability, synoptic weather, and mesoscale variability on mixed layer evolution and pumping downward of mass into the main thermocline. Spall worked with investigators at NCAR on the design of a basin scale numerical model to be used in the analysis of the moored array data. A basin-scale, non-eddy resolving, primitive equation model is used to study the large-scale processes that transfer materials and properties from the mixed layer into the thermocline. The model includes parameterizations of turbulent mixing in the near surface layer and tracer transport processes by mesoscale eddies. Atmospheric forcing fields for approximately 10 years have been derived from NCEP reanalyses and the ECMWF atmospheric weather prediction model. Direct comparisons will be made between the simulated and observed fields in the Subduction region. Issues relating to subduction at fronts have been investigated with a series of high resolution primitive equation models. Analysis with potential vorticity, passive tracers, and simulated floats is used to study higher order processes such as cross frontal exchange, subduction, eddy formation, and mixing. The

influences of large scale deformation fields on the maintenance, stability, and mean frontal structure have also been investigated.

We have found the following **results**:

Two years of high quality surface meteorological and oceanographic data from a large scale array of surface moorings in the eastern North Atlantic, making possible the analyses of the physical processes that, on large scales, carry mixed layer water into the thermocline and result in oceanic subduction.

The moored array was successful in spanning significant gradients in surface forcing. One of the two meteorological packages on the buoys, the IMET instrument, worked well in its first science deployment. Surface meteorological data was being placed on GTS to allow ECMWF and others to have access.

The Azores-Bermuda high pressure cell was shifted more to the northwest relative to climatology, with the result that northeast trades dominated the area and westerly winds were found only in the northwest corner of the domain. The pattern of the curl of the wind stress had somewhat larger scales and smaller amplitude than anticipated, but the current meter data shows that the array spanned a region of convergent flow in the mixed layer.

Surface currents (flow at 10 m relative to flow at 50 m) were largely wind-driven and showed a convergent surface flow driven by the Trades to the south and Westerlies to the north.

Buoyancy flux time series (heat flux and freshwater flux, estimated using bulk formulae and the data from the meteorological sensors on the buoys including rain gauges) were produced and compared with numerical weather prediction model data.

The annual cycle in surface fluxes yielded an annual cycle in upper ocean structure that varied across the array; the surface heating had larger amplitude peaks during the winter and summer at the northern side of the array, so that winter mixed layers were deeper and summer mixed layers shallower there.

Together with the local response, there was strong non-locally forced variability with periods of weeks was evident in the thermocline and superimposed on the annual cycle. Strong near-inertial and baroclinic tidal motion was evident in the thermocline across the array.

The observed mixed layer response (temperature and depth) at the 4 corner moorings was close to that predicted using the flux time series from the moorings and the PWP model. The response at the central mooring showed the most departure from the 1-D model hindcast; its mixed layer was deeper than predicted, consistent with a maximum in subduction in the center of the Azores-Bermuda high. Closure of the local heat budgets at each of the five sites shows that significant exportation of heat is needed at the central mooring beyond the vertical mixing processes built into PWP, while the four perimeters sites are close to a local balance. This is also consistent with a maximum in Ekman pumping near the center of the array.

The cross-frontal exchange of mass and release of potential energy resulting from baroclinic instability of the front has been accurately reproduced in a two-dimensional model with space and time dependent mixing coefficients that are derived from the properties of the large scale flow. Horizontal deformation fields (as provided, for example, by mesoscale eddies) are shown to produce mixed layer fronts consistent with those observed during the Frontal Air-Sea Interaction Experiment (FASINEX).

The Labrador Current was shown to be baroclinically unstable where it flows along the topography near Flemish Cap. Large amplitude meanders shed anti-cyclonic (low potential vorticity) eddies approximately 30-50 km in diameter with the density and water properties of upper Labrador Current Water. These eddies are entrained into the offshore barotropic deep Labrador Current near the northern edge of the Flemish Cap, where topography abruptly turns toward the south, and are carried into deep water on the offshore side of the Flemish Cap. The model results are consistent with recent observations of sub-mesoscale eddies of upper Labrador Sea Water found embedded in the deep Labrador Current.

One-dimensional mixed layer model results suggest that under severe winter conditions Labrador Sea Water can be directly ventilated in the Deep Western Boundary Current System, resulting in rapid subduction and advection to the south.

Over the course of the effort the following **transitions** of data and understanding to other efforts occurred. Use of the Subduction surface meteorological data to validate satellite and numerical weather prediction products has begun. Initial contacts have been with the National Meteorological Center (NCEP, R. Reynolds and A. Leetma) and the European Center for Medium Range Weather Forecasting (ECMWF, E. Klinker and C. Bretherton). The in-situ buoy data allows the model fields to be examined for accuracy.

Data from the moored buoys is being shared with investigators at ECMWF, NCEP, and other modeling centers as well as with satellite investigators for use in ground-truthing and validating these products.

The Subduction Central mooring carried instrumentation deployed in support of the North Atlantic Tracer Release Experiment (NATRE), and other data from that mooring was provided to NATRE investigators.

The frontal processes studied under this effort are relevant to a number of other ONR, NSF, and NOAA programs. The development of parameterizations for eddy fluxes in low resolution models is important for basin-scale models of the general circulation.

Publications completely or partially supported by this grant:

Dickey, T. D., D. V. Manov, D. A. Siegel, and R. A. Weller, 1994: Determination of net longwave heat flux at the air-sea interface using measurements from ship and buoy platforms. *Journal of Atmospheric and Oceanic Technology*, 11, 1057-1078.

Eriksen, C. C., R. A. Weller, D. L. Rudnick, R. T. Pollard, K. H. Brink, and L. A. Regier, 1991. Ocean frontal variability in FASINEX. *Journal of Geophysical Research*, 96(C5), 8569-8591.

Hosom, D. S., R. A. Weller, R. E. Payne, and K. E. Prada, 1995. The IMET (Improved METeorology) Ship and Buoy System, Journal of Atmospheric and Oceanic Technology, 12(3), 527-540.

MacWhorter, M. A. and R. A. Weller, 1991. Error in measurements of incoming shortwave radiation made from ships and buoys. Journal of Atmospheric and Oceanic Technology, 8, 108-117.

Moyer, K. A. and R. A. Weller, 1997. Observations of surface forcing from the Subduction experiment: A comparison with global model products and climatological data sets. Journal of Climate, 10, 2725-2742.

Nowlin, W. D., Jr., N. Smith, G. Needler, P. K. Taylor, R. Weller, R. Schmitt, L. Merlivat, A. Vezina, A. Alexiou, M. McPhaden, and M. Wakatsuchi, 1996. An ocean observing system for climate. Bulletin of the American Meteorological Society, 77, 2243-2273.

Pickart, R. S. and M. A. Spall, 1995. Mid-depth ventilation along the western boundary of the sub-polar gyre. ACCP Notes, II, 9-11.

Pickart, R. S., M. A. Spall, and J. Lazier, 1997. Mid-depth ventilation in the western boundary current system of the subpolar gyre. Deep-Sea Research, 44, 1025-1054.

Rudnick, D. L. and R. A. Weller, 1993: The heat budget in the North Atlantic subtropical frontal zone, Journal of Geophysical Research, 98(C4), 6883-6893.

Rudnick, D. L. and R. A. Weller, 1993: Superinertial wind-driven flow in the western North Atlantic, Journal of Physical Oceanography, 23, 2351-3708.

Spall, M. A., 1997. Baroclinic jets in confluent flow. Journal of Physical Oceanography, 27, 1054-1071.

Trask, R. P. and N. J. Brink, 1993: The Subduction Experiment. Cruise Report: R/V Oceanus Cruise Number 240 Leg 3, Subduction 1 mooring deployment cruise, 17 June - 5 July 1991, Upper Ocean Processes Group, UOP Technical Report 93-1, WHOI-93-12, Woods Hole Oceanographic Institution, Woods Hole, MA., 02543, USA, 81 pages.

Trask, R. P. and N. J. Brink, 1993: The Subduction Experiment. Cruise Report: R/V Oceanus Cruise Number 240 Leg 3, Subduction 1 mooring deployment cruise, 17 June - 5 July 1991, Upper Ocean Processes Group, UOP Technical Report 93-1, WHOI-93-12, Woods Hole Oceanographic Institution, Woods Hole, MA., 02543, USA, 81 pages.

Trask, R. P., N. J. Brink, L. Regier, and N. McPhee, 1993: The Subduction Experiment. Cruise Report: R/V Oceanus, Cruise Number 250 Legs 1 and 2, Subduction 2 Mooring

deployment and recovery cruise, 25 January - 26 February 1992. Upper Ocean Processes Group, UOP Technical Report 93-2, WHOI-93-13, Woods Hole Oceanographic Institution, Woods Hole, MA, 02543 USA, 106 pages.

Trask, R. P., W. J. Jenkins, J. Sherman, N. McPhee, W. Ostrom, R. Payne, 1993: The Subduction Experiment. Cruise Report: RRS Charles Darwin Cruise Number 73, Subduction 3 mooring deployment and recovery cruise, 30 September - 26 October 1992, Upper Ocean Processes Group, UOP Technical Report 93-3, WHOI-93-18, Woods Hole Oceanographic Institution, Woods Hole, MA., 02543, USA, 102 pages.

Visbeck, M., J. C. Marshall, T. Haine, and M. A. Spall, 1997. On the specification of eddy transfer coefficients in coarse resolution ocean circulation models. *Journal of Physical Oceanography*, 27, 381-402.

Weller, Robert A., 1991. FASINEX, A study of air-sea interaction in a region of strong oceanic gradients. *Journal of Geophysical Research*, 96(C5), 8501-8516.

Weller, R. A., D. L. Rudnick, C. C. Eriksen, K. L. Polzin, N. S. Oakey, J. W. Toole, R. W. Schmitt, and R. T. Pollard, 1991. Forced ocean response during the Frontal Air-Sea Interaction Experiment (FASINEX). *Journal of Geophysical Research*, 96(C5), 8611-8638.

Weller, R. A. and R. M. Samelson, 1991. Upper ocean variability associated with fronts. In: *Ocean Variability and Acoustic Propagation*, edited by J. Potter and A. Warn-Varnas, Kluwer Academic Publishers, pp 463 - 478.

Weller, R. A. and P. K. Taylor, 1993. *Surface conditions and air-sea fluxes: Ocean Observing System Development Panel Background Report*. JSC/CCCO Ocean Observing System Development Panel, published by Texas A&M University.

Weller, R. A., D. L. Rudnick, and N. J. Brink, 1995. Meteorological variability and air-sea fluxes at a closely spaced array of surface moorings, *Journal of Geophysical Research*, 100(C3), 4867-4883.

Weller, R. A., 1995. An introduction to the oceanography report. *Reviews of Geophysics*, Supplement, U. S. National Report to International Union of Geodesy and Geophysics, 1149-1152.

Williams, R. G., M. A. Spall, and J. C. Marshall, 1995. Does Stommel's mixed layer demon work? *Journal of Physical Oceanography*, 25, 3089-3102.

Presentations completely or partially supported by this grant:

Pickart, R. S. and M. A. Spall. Mid-depth ventilation of the western boundary current system in the subpolar gyre. European Geophysical Society, April 1995, Weisbaden, Germany.

Weller, Upper ocean response to atmospheric forcing during the Subduction experiment: Comparison of observations and 1-D mixed layer models, IAPSO/Ocean Sciences Meeting.

Weller, Surface fluxes and the upper layer. Workshop on modeling and predicting oil spill trajectories, Univ. of Massachusetts at Dartmouth.

Moyer and Weller, Observations of surface forcing from the Subduction experiment and TOGA COARE: A comparison with global model products and climatology. Workshop on in-situ validation of numerical weather prediction models at ECMWF, Reading, England.

Weller, Observations of surface forcing from the Subduction experiment and TOGA COARE: A comparison with global model products and climatology. With Kerry Moyer and Steven Anderson. Eighth Conference on Air-Sea Interaction and GOALS Symposium at AMS Annual Meeting, Atlanta.

Weller, In-situ air-sea flux measurements: their role in CLIVAR. Ocean CLIVAR planning meeting, San Antonio.

Williams, R. C., M. A. Spall, and J. C. Marshall. Subduction of water masses and tracers: What is the impact of eddy stirring? The XXI General Assembly of the International Association for the Physical Sciences of the Oceans, 5-12 August, 1995. Honolulu, HI.